Quantum-Classical Correspondence in the Brain: Scaling, Action Distances and Predictability behind Neural Signals

Gustav BERNROIDER¹* and Sisir ROY^{2,3}

¹Department Organismic Biology, Neuroethology, University of Salzburg, 5020 Salzburg, Austria ²School of Computational Science, George Mason University, Fairfax, VA 22030, U.S.A. ³Indian Statistical Institute, Kolkata, India *E-mail address: Gustav.Bernroider@sbg.ac.at

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Abstract. Quantum models of higher level brain functions such as conscious experience, suggest that the neural correlate of mentation requires dynamical properties instantiated at the Planck-scale. Several candidate quantum processes have been suggested, but it remains to be seen how these quantum properties can relate to the established classical signals in the brain involving physical action twenty magnitudes above the quantum domain. In this paper we show the results of a systematic analysis of Lagrangian action order to brain processes at different scales of resolution. The results encompass processes at the macroscopic single cell level to processes at the sub-molecular and concerted molecular population level. It is shown that the state of ions in the permeation filter of channel proteins, as for example indicated by the MacKinnon KcsA K⁺ channel model, is a quantum phenomenon involving a Lagrangian in the order of 10^{-34} Js. Further, we show that the brain spans at least 20 orders of magnitudes of physical action with physiologically significant signal properties. We suggest that the quantum-classical correspondence in the brain is resolved by the spread of quantum-witness states that correlate with the gating states of voltage sensitive ion channels.

1. Introduction

The classical neural doctrines as formulated by BARLOW (1972), state that the spatiotemporal variation of basically identical oscillations of membrane potentials (action potentials) provided by nerve cells is a complete description for the functional understanding of the nervous system including all phenomena of mentation. These doctrines deposit a considerable amount of discomfort and entail some obstinate problems, causing an increasing number of neuroscientists to question the dogma (e.g. reflected by the conference research abstracts, TUCSON, 1994–2004). The list of problems is large and deserves some classification. From the most basic ontological level, it is hard to see why and how electrical events should become "equated" with the phenomenology behind mentation, i.e. the conscious experience of qualia (how it feels to be in a certain "state"). In the view of

CHALMERS (1995), the states of mentation such as consciousness do not logically supervene on the physico-chemical organization of the brain. From the physical perspective, Barlow's doctrines imply "*response selectivity*", i.e. all "sensation" stems from real-time observations of the activity of our own neurons, responding to a particular sensory signal (BIALEK *et al.*, 1991). However, as, among others, Mogi has convincingly pointed out, it is impossible to establish response selectivity of a particular neuron if simply based on the activity rate of the neuron at a given time (MOGI, 1997). Moreover, the same stimulus applied repeatedly causes responses with variability as large as the response itself (ARIELI *et al.*, 1996). All we have, are *correlations* between the activity of a set of neurons, "selected" by a completely unknown process, with properties from "stimulus space", selected by a third person human observer. So, in the context of the stated classical neural doctrines, any causation of the mind-brain relation remains obscure and the dogma can hardly be passed on as an immutable fact.

It is within this landscape of burning questions that an increasing number of researchers have started to argue that a plausible description of brain function may require nonclassical physical descriptions employing the concepts of quantum mechanics (QM) (STAPP, 1993, 1996; HAMEROFF and PENROSE, 1996; BERNROIDER *et al.*, 1996). But why should QM offer solutions to the above mentioned questions, that can not be provided by classical physics (or physiology)? This question is at the center of attention in the present work.

2. Why Quantum Physics in the Brain?

One obvious answer would be that classical physics ignores the role of an observer, i.e. the brain, whereas the ontology behind QM has traditionally been concerned with interpretation and correspondence problems from it's very beginning (e.g. in EVERETT, 1957; BOHR, 1961; HEISENBERG, 1963; WHEELER and ZUREK, 1983) and has allowed the development of QM concepts that explicitly figure observership in a non-system's view, e.g. in David Bohm's QM interpretation (BOHM and HILEY, 1993), discussed in the present context by BERNROIDER (2003a).

An even more pressing motivation to involve QM in brain science is the overwhelming and widespread analogy of properties specific to QM and the "neuro-psychology" behind brain phenomena such as perception. For example the unique feature behind QM is "*entanglement*", a between system coherence of states that survives physical separation, giving rise to the "non-local" character of QM. Perception in the brain works very similarly. Although perception is coded locally, by the highly segregated firing activity of neurons responding selectively to perceptual features, the percept as such, at every instant of "psychological time" occurs "non-locally", displaying a yet unresolved "hidden wiring" that "locks" the percept to those states that are engaged in the coding of it's features (such as colour, shape, location, etc.). This is the "binding problem" behind perception (VON DER MALSBURG, 1981) and has allowed Ken Mogi for example to suggest "Mach's Principle in Perception" (MOGI, 1997). A good illustration of this analogy, originally proposed by WOLF (1981) and recaptured by MONROE (2002) is given in Fig. 1.

Yet another "analogy" between QM and brain phenomena becomes striking, when we look at the parallelism behind signal propagation in the brain. The best way to envisage the



Fig. 1. The perception analogy to quantum entanglement. (a) The two perspectives of a cube (top or bottom) represent two exclusive states of a system (the cube). While our perception (="a measurement") of the cube will always either give $|0\rangle$ (e.g. top view) or $|1\rangle$ (e.g. bottom view), the quantum analog of the system (a "qubit") can be in both states simultaneously, expressed as $c_0|0\rangle + c_1|1\rangle$, the superposition of both states (analog to the transparant cube at the top). (b) A between system (cubes) superposition of states demonstrates *entanglement* (a state of non-local super-correlation that can only be found in quantum-systems): the above entangled state could be expressed as $|\psi_{cube}\rangle = c_0|0_10_20_30_40_5\rangle + c_1|1_11_21_31_41_5\rangle$. In analogy to perception, if we observe one cube in the top-view position, all other cubes will instantaneously lock into the same perspective (WOLF, 1981; MONROE, 2002). Note: although entanglement involves the state of many, distributed systems, the action necessary to "undo" these states is the same as observing a single cube—this point plays a decisive role in the context of this paper (see Secs. 5 and 6).

spread and exchange of signals in a "real brain" is not provided by the "reduced connectivities" behind artificial neural networks, but by the holographic model proposed in the pioneering work of PRIBRAM (1991). Simply speaking, the spread and interactions of electromagnetic signals along dendrites and axons can best be described if one replaces the conducting membrane manifold by rays of light. By doing so, propagating potentials carry a *phase property*, which is indispensible for the composition of action potentials into oscillating, "wave-like" phenomena as observed to underlay many "cognitive events" (NICOLELIS *et al.*, 1995; ROLEFSEMA *et al.*, 1997). Modelling neural signaling along this way entails the use of *complex wavefunctions* corresponding to definite states of linear motion, characteristic for the directed spread of potentials along axons, again analogue to the formalism used in quantum mechanics (BERNROIDER *et al.*, 1996).

Despite many reasons why QM may play a decisive role in the functional explanation of brain function (explaining how the brain is engaged in mentation), we have not yet identified the precise nature of the quantum system involved and have not shown how this quantum process relates to the established classical signaling in the brain. Two things must be done: (i) the process or state must be identified and (ii) it must be shown that this quantum event is in fact reponsible for and compatible with the established classical dynamics of the brain. For example, in this context ROY and KAFATOS (2003) have recently discussed the geometro-dynamic consequences of applying the "field" concept to brain

signaling. There, one decisive question is, how the brain codes the space-time behaviour of an object in motion. PELLIONISZ and LLINAS (1982) have focused on this question and argue, that as the conduction speed varies in different types of axons, the concept of simultaneity from a physical perspective (e.g. in Einstein's special theory of relativity) is not compatible with the way the brain organizes it's signals. These authors proposed a geometric structure known as functional geometry to understand the activity of the brain. The contribution of ROY and KAFATOS (2003) provided a probabilistic framework for the geometric structure on a global scale, that is over the surface of all cortical areas. In fact space-time geometries compatible with the unique functional geometry of the brain shed new light on the highly debated Orchestrated Objective Reduction (OrchOR) model fowarded by HAMEROFF and PENROSE (1996). In this proposal QM-states carry their own space-time geometries and spontaneous quantum state reductions in the brain are associated with conscious events. However, as the authors also point out "... the model still suffers from being dependent upon certain speculative ideas which have yet to be demonstrated" (PENROSE, 2003).

3. A Neural "Correspondence Problem"

In the "systems view" of physics (as opposed to the "prespace" concept of BOHM), one considers the Universe as a collection of open and interacting quantum systems. The central question then is "why does the quantum universe appear classical?" An extensive and deep treatment from the perspective of physicalism has recently been offered by Wojciech H. Zurek in his *Existential Interpretation* (PAZ and ZUREK, 2000; ZUREK, 2001). However, there the role of the brain is left out. One reason may be that in physics, the entry of ill-posed anthrophic attributes quite often produces more problems than solutions and the role of the brain in QM and vice versa awaits to be resolved. *But, the de facto separation of the universe into observers and systems—instantiated by the existence of our brain—and the fact that the "final observer" is the brain, can never absolve physics from dealing with the brain.*

Here we focus on the functional relation of physics to the phenomenal involving the brain and, at a somehow lower level, address the question from the view of the long disputed *correspondence problem*, i.e. the relation between the quantum domain and the classical domain. The view adopted is different from previous ones in several aspects: we argue that, if it can be shown, that quantum processes are essential for higher level brain function such as thinking and perceiving, then it becomes plausible that the quantum origins of "classical reality" are inseparably associated with the "observing" human brain. In the systems view the observer would still be an open quantum system that acquires, stores and processes information, but in contrast to the "Existential Interpretation" e.g. the version suggested by Zurek, the observer is different from what he/she knows. "Knowing" already implies classicality, the aftermath of quantum system interactions, when the "observed" system states have spread through the "environment" of quantum brain states. The resulting brain states are the "witness states" from which the brain can infer the original quantum state of the system that has caused the observed "redundancy", or, as Wojciech Zurek has phrased it, "the widespread advertising" of these states. We propose that inference to the contents of information behind the original quantum state becomes

"aware", but at the sacrifice of "objective truth", as the brains organization constrains the spread of system states under observation to "*preferred states*", provided by the nature of the interacting brain Hamiltonian (signal segregation at the quantum level). Thus, organizational constraints imposed by the brain on the spread of witness states organize the aftermath of quantum state interactions and the emergence of "classicality" in the brain. This provides the basis of individuality or "privacy" of perceptual experience and the process itself can be regarded as the "neural process correlate of conscious experience" (NCC). It will be discussed in more detail in relation with the concept of "*action distance*" below.

Two issues become essential at this stage of discussion: i) "observation" by the brain at the quantum level inevitably leads to the destruction of coherent quantum superpositions of basis states (*decoherence*) and is subjected to *complementarity* and ii) the observed classical "reality" that provides the physical instantiation of conscious experience, emerges through "*correlations*" between the spreading neural witness states and the quantum-brainstate under observation. How the brain might deal with the issue of complementarity has been treated by the authors in previous papers (BERNROIDER, 1999; ROY and KAFATOS, 2003, ROY, 2003) and a possible consequence of the complementarity principle in cognition processes has been suggested by the second author (ROY and KAFATOS, 1999). The latter point "spreading through correlations" implicitly contains the question of "*predictability*" and the "seeds" for random fluctuations behind all neural activities, if monitored from the view of an external observer (the records made by the neurophysiologist). We will address this question separately because of it's significance for the long debated question about "noise in the brain".

4. Dimensional Analysis of Neurophysical Processes

Lagrangian action can be expressed as integrals over magnitudes that conserve the integrand along spatio-temporal translations. This *principle of invariance* applies for example to energy (*E*) along the dimension of time (*T*), $A = E \cdot T$, or momentum (*P*) over space (*L*), $A = P \cdot L$, implying the dimension of (mechanical) action *A* as

 $[action] = [mass] \cdot [length]^2 \cdot [time]^{-1}$ or $A = M \cdot L^2 \cdot T^{-1}$

with one unit as "the Lagrange": $1 L = 1 \text{ kg} \cdot \text{m}^2 \cdot \text{s}^{-1} = 1 \text{ J} \text{ s} \cong 10^{34} \hbar$ and $\hbar = 2\pi \cdot h$, with h denoting Planck's constant. If this action turns out to scale along Planck's constant $\hbar/2\pi$, the physics behind it is generally considered to require a quantum notation. Dimensional analysis explores the physics behind a system in the most natural standard of action and allows the expression of action by the combination of many different physical magnitudes, i.e. those observables most suitable to describe the state of the system (see Appendix 1 for details).

At the Quantum Mind Conference 2003 (Tucson, March 15–19, USA) one of the authors showed the results from a systematic application of the *Lagrangian concept of action order* to brain processes at different scales of resolution, to help to clarify the dispute whether quantum phenomena are important in brain science (BERNROIDER, 2003b). Some results are summarized in Table 1.

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Source/Action	Mechanical units	Energy/Time	Electrical units
	$(A = M \cdot L^2 \cdot T^{-1})$	$(A = E \cdot T)$	$(A = C \cdot V \cdot T)$
Cell/Action potential Molecular/Ion permeation	$\begin{array}{c} 1.8 \times 10^{-15} \ L \ (Js)^{(1)} \ (kg \ m^2 \ s^{-1}) \\ 0.48 \times 10^{-34} \ L \ (Js) \end{array}$	$6 \times 10^{-16} \text{ L} (\text{Js})^{(2)}$ $6.95 \times 10^{-33} \text{ L} (\text{Js})^{(3)}$	$\begin{array}{c} 2.1 \times 10^{-16} \ L \ (Js)^{(2)} \\ 7 \times 10^{-33} \ L \ (Js)^{(3)} \end{array}$

⁽¹⁾Time (T) at the scale of spiking, i.e. 10^{-3} s.

 $^{(2)}T$ corrected to be close to 10^{-8} s for max conduction of ions.

 $^{(3)}T$ assumed to scale along 10^{-12} s, the minimum transition time in oxygen coordination by potassium ions (GUIDONI and CARLONI, 2002).

Cellular level: Propagating action potentials, depolarizing the entire cell membrane, are traditionally seen as the "carriers" of the neural code. Together with the Neuron Doctrine (ADRIAN, 1928), this addresses the cellular states of membrane polarization as the only "objective functional" states of the brain. From Table 1 the physical action orders behind these states, as seen from mechanical units, from an energetical point of view and using electrostatic units, are available. Data are based on an idealized 1 cm unmyelinated squid axon with diameter d = 1 mm, and signal composition according to the Hodkin-Huxley (HH) model (HODGKIN and HUXLEY, 1952). Expressed in mechanical units (total mass of ions moving in and out the cell membrane during a characteristic(propagation) time $T = 10^{-3}$ s), the action $A = M \cdot L^2 \cdot T^{-1}$ gives $1.8 \cdot 10^{-15}$ L which is roughly $\approx 10^{19} \cdot \hbar$, that is 19 magnitudes of order above Planck's constant. From an energetical point of view, i.e. using $A = E \cdot T$, with E the energy dissipated per mole of ions, according to $E = zF \cdot (E_{ion} - V_m)$, with z the valence of ions, F the Faraday constant (9.648 \cdot 10⁴ C mol⁻¹) and V_m the membrane resting potential of -77 mV, we obtain a "mean driving force" between the different ion species involved (Na⁺ entry and K⁺ extrusion) of $6 \cdot 10^3$ J/mole and A gives $6 \cdot 10^{-12}$ L (Js). Finally, action from *electrostatic magnitudes*, with the capacity $C = 2.2 \cdot 10^{-8}$ C and voltage and time as before, $A = C \cdot V \cdot T = 2.1 \cdot 10^{-11}$ Js (L).

With the rough assumptions made, the energetical and electrostatic estimation of action order are comparable, but are $\sim 10^3 - 10^4$ above the action obtained by a momentum-space (mechanical) representation. The reason for this can be found to be due to the choice of the *characteristic time* of these events, i.e. the temporal scale along which energy remains invariant. From an energetical or electrostatic point, physical action involves the transfer of ions through single ion channel proteins. Therefore it is more natural to choose the characteristic transit time of ions through voltage sensitive ion channels, and this time scales along 10^{-8} s (HILLE, 1992). Furnished with this time, the electrostatic action $A = C \cdot V \cdot T$ gives $2.1 \cdot 10^{-16}$ L which is in the range of the momentum-space estimation.

Taken together, dimensional analysis of cellular signalling, based on the Lagrangian concept of action, reveals comparable action orders from three independent, but empirically pertinent concepts of action, at the scale of $\sim 10^{-15} - 10^{-16}$ Js (L). This is 18–19 magnitudes above the "quantum-scale" of $\hbar \approx 1.054 \cdot 10^{-34}$ MKSA units.

Thus the neuron-doctrines are definitely classical and the physical analysis of action potential propagation does not require any quantum concept. Furthermore, if these results are compared with an estimated neural state decoherence time, as given by TEGMARK (2000), one finds a very good agreement with the present findings. *Decoherence* is the destruction of quantum coherent superpositions due to an interaction with the environment. Tegmark has calculated the timescale on which decoherence can be expected to destroy superpositions of states realized across the membrane thickness of order ~10 nm. The timescale turns out to be between 10^{-19} to 10^{-20} s. If this is compared with the characteristic or dynamical time scale of the underlaying process (i.e. the firing of neurons) of 10^{-3} to 10^{0} s, one finds that the difference between decoherence time and dynamical time is of order 10^{19} , the same difference as predicted by the present dimensional analysis between the quantum scale and the action order behind spiking!

Molecular level: Already Hodkin and Huxley predicted two types of processes associated with the spread of membrane potentials; *permeation* of ions and "gating", i.e. the control of access of ions to the permeation pathway (reviewed by ARMSTRONG and HILLE, 1998). During the recent years R. MacKinnon's group has provided an atomicresolution picture down to 0.2 nm Bragg spacing by X-ray crystallography of model voltage-dependent cation channels (ZHOU et al., 2001; MORAIS-CABRAL et al., 2001). Together with subsequent work on the underlaying dynamics and energetics of permeating ions, this allows a detailed insight into the delicate atomic interactions associated with access and selective permeation of ions through charged membranes. The channels can pass at least 1 pA of current, corresponding to 10⁸ monovalent ions per second, while maintaining selectivity to a particular ion species. The single charge transfer involves masses of $3 \cdot 10^{-26}$ kg, a transmembrane passage extending in the range of $4 \cdot 10^{-9}$ m (3.4 nm in Streptomyces lividans potassium channels, DOYLE et al., 1998) and a dynamical time of 10^{-8} s. This provides a "mechanical" action $A = M \cdot L^2 \cdot T^{-1} = 0.48 \cdot 10^{-34} L \sim \hbar$ (Planck scale). This simple estimation is based on empirically established ion conduction properties and yields precisely the dimensional scaling characteristic for quantum processes: Ion permeation is a quantum-chemical process!

5. Bridging the Levels

Having established that the translocation of single ions through the permeation pathway of ion channels is a quantum process, the question is how do the corresponding quantum state functions relate to the classical membrane voltage and, most importantly, what is the functional significance of such "subthreshold regimes", i.e. physical states 20 orders of magnitude below classical firing activities?

Channel counting may provide the answer. The quantum-classical transition in the brain seems to be tied up in the redundancy and behaviour of ion-channel system states. As mentioned above, these can be seen as representing the "witness states" of between systems interactions (object, subject and environment) originating from the quantum scale. The decomposition of systems used in the present outline is illustrated in Fig. 2. The view holds that high channel numbers are connected with i) more stable values of the resting membrane potential, ii) higher axonal conduction velocities and iii) increased "signaling reliability" (for a review see WHITE *et al.*, 2000).

Whereas the first two aspects belong to the (classical) properties of non-linear channel conductances above firing threshold, the last aspect critically involves sub-threshold aspects and the issue of *noise*. The source of noise is often attributed to the stochasticity

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Fig. 2. The systems view: subsystems in the brain. In the context of the present paper, the system under consideration (S) is provided by the ions (K⁺ or Na⁺) within the permeation path of the channel protein. The environment (E) is given by the channel protein—a specific part of this environment is considered as the apparatus (A), provided by 5×4 in plane carbonyl oxygens surrounding and interacting with the ions in the channel permeation path, according to the MacKinnon KcsA K⁺ channel model. The possible states of E are closed or open—the gating states of the channel entrance. With closed states, right, the *interaction Hamiltonian* H_{SA}, between the system and the apparatus is much larger than H_{SE}, the interaction Hamiltonian between the system and the environment (e.g. high or low ion concentrations). It is suggested that this "von Neumann isolation of the system" guarantees sufficient time for within state superpositions of ion-oxygen interactions, so that the evolution of one ion-state can depend on the other. According to the present model this time (sometimes called decoherence time) will have the same temporal extension as the between gating state of ion channels, i.e. along 10^{-3} s.

of voltage-gating in single channels (WHITE and HAAS, 2002) and found to be proportional to $N^{-1/2}$ under stationary conditions (where *N* is the number of channels). This is compatible with the view that "reliability" or "predictability" of signals increases with the number of states that are most redundantly spread within the environment provided by a specific functional organization of the brain. Two measures of emerging reliability in the "aftermath" of quantum system decoherence have been suggested (ZUREK, 2001): i) *action distance*, i.e. the total action necessary to distinguish between states of the brains environment (the states of gating in ion channels) that correspond to different states of the system (e.g. the ions in the permeation pathway of channel proteins and ii) *redundancy*, i.e. the number of times information about the system can be extracted from the environment. If the gating state of channels is either closed or open (0 or 1), we have 2^N possible state configurations composed from *N* channels forming the "environment" for ions.

The states of this environment (ε_0 and ε_1), correlated with the states of the system (states of ions, \uparrow and \downarrow , e.g. corresponding to the oxygen coordination states S₈, S₆ in the MacKinnon model) can be written as:

$$|\psi_{S\varepsilon}\rangle = \alpha |\uparrow\rangle |00 \quad 0\rangle + \beta |\downarrow\rangle |11 \quad 1\rangle \tag{1}$$

and the action necessary to discriminate the *N*-states of the environment, corresponding to the different states of the system:

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$$\Delta(|\varepsilon_{\uparrow}\rangle, |\varepsilon_{\downarrow}\rangle) = N(\pi/2 \cdot \hbar). \tag{2}$$

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Action distance is critically dependent on the definition of subsystems from Hilbert space. For example, the system states $|\uparrow\rangle$ and $|\downarrow\rangle$, reflecting the internal electronic states of potassium ions within the permeation pore of KcsA K⁺ channels in the MacKinnon model (MORAIS-CABRAL *et al.*, 2001), are provided by the coordination with either six oxygens from the surrounding four carbonyl-groups and two intermittant water molecules, or by the eight oxygens from neighbouring "carbonyl-planes". These internal system states can be discriminated by two different environmental conditions: i) by the "gating state" of, say *N* ion channels, as the open or closed gates are correlated with six or eight oxygen coordinations, or ii) by the five in-plane oxygen arrangements surrounding each channels permeation path. In the first case "*N*" is provided by the number of ion channels making up the "record states" of the whole environment (*between channel action distance*), whereas in the second case we can set N = 20 oxygens engaged in K⁺ coordination within each channel (*within channel action distance*).

5.1. Within channel action distance The prediction from Eq. (2) is

$$\Delta(|\varepsilon_{\uparrow}\rangle, |\varepsilon_{\downarrow}\rangle) = 20(\pi/2 \cdot \hbar) \approx \pi \cdot 10^{-33} \text{ L} (Lagrangian units). \tag{3}$$

From molecular dynamics free energy simulations (MDS) of ion state transitions within the KcsA K⁺ channel, we obtain a transition energy of 1 kcal for the ion coordination states (BERNECHE and ROUX, 2001) and a transition time in the range of 10^{-12} s (GUIDONI and CARLONI, 2002). This lets us estimate the physical action behind these state transitions in the coherent MKSA system to be $[A] = [E] \cdot [T] = 0.695 \times 10^{-32} \text{ Js} \approx 2\pi \cdot 10^{-33} \text{ L}$ which is very close to the prediction made by our model and within the range of quantum-scales.

5.2. Between channel action distance

The subsystems are given by ion channels and the choice of *N* depends on the definition of the total system under consideration. If the system is confined to a *single cell*, channel counting on particular model cells suggests *N* to be close to 10^8 channels for a mammalian entorhinal cortex cell (WHITE *et al.*, 2000) and about 10^{10} channels in the unmyelinated squid neuron. Confined to the total membrane surface of a single cell, this suggests action distances between $[A] \approx (\pi/2) \cdot 10^{-26}$ and $(\pi/2) \cdot 10^{-24}$ to distinguish the closed and open states of channels that correspond to the internal states of ions in the permeation path.

If the total system is taken to be provided by *the ensemble of nerve cells* engaged in a single percept, i.e. the set of cells selected by *interaction simultaneity* as suggested by MOGI (1997), we can estimate the corresponding action distance as follows:

From an average density of cortical cells in the range of 10^4-10^5 /mm³ (numbers from BRAITENBERG and SCHUZ, 1991), the total number of cells/brain in the range of $10^{10}-10^{11}$ cells, and the "visual segregation volume" (ZEKI and SHIPP, 1988; ZEKI, 1990; UNGERLEIDER, 1995; VOGGENHUBER, 2002) making up to 70% of sensory neo-cortex, it seems to be reasonable to expect at least 0.5×10^{11} cells to be engaged in a conscious visual percept.

Taking the above channel counts/cell of a typical cortex cell, this gives:

$$\Delta(|\varepsilon_{\uparrow}\rangle, |\varepsilon_{\downarrow}\rangle) = (\pi/4 \cdot \hbar) \cdot 10^{19} \approx (\pi/4) \cdot 10^{-15} \text{ L.}$$
⁽⁴⁾

We have now recovered precisely the same physical action order that is characteristic for propagating action potentials at the cellular level, 1.8×10^{-15} L, as seen from the above paragraph 4, but this time using a quite different approach and concept, setting out from a quantum scale metric (action distance) for channel ion states. This coincidence of action orders will only apply to densely packed, large volume and extensively segregated brain structures, such as the primate or avian forebrain.

To obtain the above result we have also used channel counts based on radioactive binding studies (LEVINSON and MEYES, 1975; CONTI *et al.*, 1975), rather than on maximum conductances of open channels. With a maximum conductance of up to 1 pA (10^5 ions moving per msec), action potentials could propagate by involving just ~ $4 \cdot 10^3$ - $6 \cdot 10^3$ channels/cell in the MEC (mammalian medio-entorhinal cortex cell) model (ALONSO and LLINAS, 1989). This indicates a yet unexplained *redundancy* of channels—with up to $2 \cdot 10^4$ more channels/cell than are actually required for impulse propagation.

6. Implications and Conclusion

Action distance provides a measure for *information-theoretic redundancy* emerging from the aftermath of decohering quantum sub-systems. The remarkable redundancy of voltage-gated ion channels that is revealed by studying action distances between ion channels merits further considerations, in particular in view of the highly demanding metabolic budgets associated with this redundancy. Based on the present concept we suggest that the observed redundancy of channels is a reflection of "*predictability*" within the quantum-classical correspondence in the brain. It is plausible that in the brain the division into subsystems providing the "environment" for "ion-channel quantum states" is realized by the (costly) organization of a large number of voltage-gated ion-channels. The functional partitions behind signal segregation at the classical neuronal level, a key to the macroscopic organization of neo-cortex, can then be seen to maximize this redundancy, that is to maximize the total number of copies of the information given by an ion-quantum state that exists within the brain.

The partition of the environment into ion-channels hosting the quantum system states is non-overlapping, so one can expect to be able to extract the information about the system (the ion-coordination states) by scanning just single fragments of this environment. The most natural fragment of the environment is the state of membrane polarization along a single nerve cell. This makes the classical action potential, depolarizing the entire patch of an axon, to the most obvious candidate "measurement" process that reads out the "witness states" correlated with the initial quantum states of the system according to Eq. (1). I suggest that the propagating potential flips one-by-one channels, that is n < N subsystems of the environment by changing the gate states of voltage-gated channels. This is compatible with the result expressed in Eq. (4), where the entire action distance to undo the Nsubsystems of the environment has been found to be on the same order as the action behind the propagation of an action potential along a single cell (see Fig. 3 for the correlations between action order and QM-action distance).



Fig. 3. Scaling the correlations in the brain. A possible relation between physical action order expressed in magnitudes of ten and predicted quantum-action distance as suggested in text. Overall, there appears to be a rather regular difference in the scaling of action along different organizational levels in the brain, in the order of 10¹⁰. Based upon present results there appears a remarkable scaling relation between physical action order of brain signals and action distance between entangled states of the brain. The physical action behind a propagating action potential confined to the axon of a single cell is of the same magnitude of action that is necessary to discriminate the quantum states of an entire cell ensemble. The action of gating seems to be very close to the action distance along the channels of a single nerve cell. Thus "reading out" a single nerve cell by a propagating wave of channel state changes (the action potential) requires the same action as it needs to undo the quantum states of all cells engaged in a particular situation (e.g. percept).

As a consequence, a remarkable relation in the brain between "physical effort" (action order) and state-correlations emerges. The states of ions in the permeation path are "advertised" by the redundancy of channel states among nerve cells. After the correlations between system states have spread, say among *N* environmental systems, it seems to be sufficient to intercept just *n*-channels confined to a single cell in order to infer the history of the system (i.e. the states of ions originally prepared). Thus "interaction simultaneity" between the activity of many sensory cells engaged in a conscious percept could likely require the "post-hoc consultation" of the sequence of open-or closed channel states of just a single cell. It is this "post-hoc consultation" of just a small fragment, possibly just one cell of the ensemble behind the perceptive process that allows an unperturbed recovery of the aftermath of decoherd ion-quantum states. A number of testable predictions can be expected from this conjecture. Albeit still speculative, we suggest that the quantum-classical correspondence discussed in this paper establishes an important aspect of the highly debated neural correlate of consciousness.

Appendix 1: Dimensional Analysis

Setting out from the definition of mechanical action

$$[action] = [mass] \cdot [length]^2 \cdot [time]^{-1}$$
 or $A = M \cdot L^2 \cdot T^{-1}$

action can be expressed by the combination of many different physical magnitudes, e.g. as

$$A^{2} = (M \cdot L^{2} \cdot T^{-1})^{2} = (M \cdot L^{2} \cdot T^{-2}) \cdot M \cdot L^{2} = E \cdot M \cdot L^{2},$$

providing action in terms of energy, mass and length. Another useful expression involves angular frequency $\omega = 1/T$ which gives an action $A = E/\omega$. Also electrical quantities make up an action that can be expressed in purely mechanical units: with a capacity *C* and a potential *V* one obtains an energy *C*·*V* and action $A = C \cdot V \cdot T$ with one unit of charge e = $1.602 \cdot 10^{-19}$ *C* derived from Coulombs law in the cgs electrostatic system. From the fundamental constant of electrostatics $1/4\pi\varepsilon_0$ and the Coulomb force $F = (1/4\pi\varepsilon_0) \cdot (q_e^{-2}/r^2)$ one finds the dimension of the constant

$$[1/4\pi\varepsilon_0] = [(L^2 \cdot F)/C^2] = [L^2 \cdot (M \cdot L \cdot T^{-2})(1/C^2)] = [L^3 \cdot M \cdot T^{-2} \cdot C^{-2}],$$

thus $[q_e^{-2}/(4\pi\epsilon_0)]$ has dimension $[L^3 \cdot M \cdot T^{-2}]$ and as voltage can be expressed as [E/q] which gives $[L^{-1}]$, the electrostatic action $A = C \cdot V \cdot T$ provides action in purely mechanical units as $A = M \cdot L^2 \cdot T^{-1}$.

REFERENCES

- ADRIAN, E. D. (1928) The Basis of Sensation, Christophers, London.
- ALONSO, A. and LLINAS, R. R. (1989) Subthreshold Na⁺ dependent theta like rhythmicity in stellate cells of entorhinal cortex layer II, *Nature*, 342, 175–177.
- ARIELI, A., STERKIN, A., GRINVALD, A. and AERTSEN, A. (1996) Dynamics of ongoing activity: Explanation of the large variability in evoked cortical responses, *Science*, 273, 1868–1871.
- ARMSTRONG, C. M. and HILLE, B. (1998) Voltage gated ion channels and electrical excitability, *Neuron*, **20**, 371–380.
- BARLOW, H. (1972) Single units and sensation: A neuron doctrine for perceptual psychology, *Perception*, 1, 371–394.
- BERNECHE, S. and ROUX, B. (2001) Energetics of ion conduction through the K⁺ channel, *Nature*, **414**, 73–77.

BERNROIDER, G. (1999) On form, mind and matter (with special reference to 'Crystal Souls' by Ernst Haeckel, translated by A. L. Mackay), *FORMA*, **14**, 185–198.

- BERNROIDER, G. (2003a) Quantum neurodynamics and the relation to conscious experience, *NeuroQuantology*, **2**, 163–168.
- BERNROIDER, G. (2003b) Dimensional Analysis of Neurophysical Processes Related to Mentation, Quantum Mind 2003, Tucson, U.S.A., http://www.consciousness.arizona.edu/quantum-mind2/
- BERNROIDER, G., RITT, F. and BERNROIDER, E. W. N. (1996) Neural phase-time coding from the view of an electrodynamic perturbation problem, *FORMA*, **11**, 141–159.
- BIALEK, W., RIEKE, F., DERUYTER VAN STEVENINCK, R. R. and WARLAND, D. (1991) Reading a neural code, Science, 252, 1854–1857.
- BOHM, D. and HILEY, B. (1993) The Undivided Universe, Routledge, London.
- BOHR, N. (1961) Atomic Physics and Human Knowledge, Science Editions, New York.
- BRAITENBERG, V. and SCHUEZ, A. (1991) Anatomy of the Cortex: Statistics and Geometry, Springer Verlag.

CHALMERS, D. (1995) Facing up to the problem of consciousness, J. Consciousness Studies, 2(3), 200-219.

- CONTI, F., DEFELICE, Ø. and WANKE, E. (1975) Potassium and sodium ion current noise in the membrane of the squid giant axon, J. Physiol. (London), 248, 45–82.
- DOYLE, D. A., MORAIS CABRAL, J., PFUETZNER, R. A., KUO, A., GULBIS, J. M., COHEN, St. L., CHAIT, B. T. and MACKINNON, R. (1998) The structure of the potassium channel: Molecular basis of K⁺ conduction and selectivity, *Science*, 280, 69–76.
- EVERETT, H. (1957) The Theory of the Universal Wave Function, Princeton Univ. Dissertation, reprinted in DEWITT, B. S. and GRAHAM, N. (1973) The Many Worlds Interpretation of Quantum Mechanics, Princeton Univ. Press.
- GUIDONI, L. and CARLONI, P. (2002) Potassium permeation through the KcsA channel: a density functional study, *Biochimica et Biophysica Acta*, **1563**, 1–6.
- HAMEROFF, St. and PENROSE, R. (1996) Conscious events as orchestrated space-time selections, J. Consciousness Studies, 3(1), 36–53.
- HEISENBERG, W. (1963) Physics and Philosophy, Allen and Unwin, London.
- HILLE, B. (1992) Ionic Channels of Excitable Membranes, Sinauer Assoc. Inc., Sunderland, Mass.
- HODGKIN, A. L. and HUXLEY, A. F. (1952) A quantitative description of membrane current and its application to conduction and excitation in nerve, *J. Physiol (London)*, **117**, 500–544.
- LEVINSON, S. R. and MEYES, H. (1975) The binding of tritiated tetrodotoxin to squid giant axons, *Phil. Trans. R. Soc. London B*, **270**, 349–352.
- MOGI, K. (1997) Response selectivity, neuron doctrine and Mach's principle in perception, Austrian Soc. For Cognitive Science Tech Report, 97-01, 176–183.
- MONROE, C. (2002) Quantum information processing with atoms and photons, Nature, 416, 238-246.
- MORAIS-CABRAL, H. J., ZHOU, Y. and MACKINNON, R. (2001) Energetic optimization of ion conduction rate by the K⁺ selectivity filter, *Nature*, **414**, 37–42.
- NICOLELIS, M. A. L., BACCALA, L. A., LIN, R. C. S. and CHAPIN, J. K. (1995) Sensorimotor encoding by synchronous neural ensemble activity at multiple levels of the somatosensory system, *Science*, 268, 1353– 1358.
- PAZ, J. P. and ZUREK, W. H. (2000) Environment-Induced Decoherence and the Transition from Quantum to Classical, Course Lectures, Les Houches Summer School on 'Coherent Matter Waves', arXiv:quant-ph/ 0010011 v1.
- PELLIONISZ, A. and LLINAS, R. (1982) Space-time representation in the brain: The cerebellum as a predictive space-time metric tensor, *Neuroscience*, 7, 2949–2970.
- PENROSE, R. (2003) Testing the Physical Basis of the Orch-OR Model of Consciousness, Quantum Mind 2003, Tucson, Arizona, U.S.A., http://www.consciousness.arizona.edu/
- PRIBRAM, K. H. (1991) Brain and Perception, Lawrence Erlbaum Assoc. Publ.
- ROLEFSEMA, P. R., ENGEL, A. K., KOENIG, P. and SINGER, W. (1997) Visuomoto integration is associated with zero time-lag synchronization among cortical areas, *Nature*, **385**, 157–161.
- ROY, S. (2003) Planck Scale Physics, Pregeometry and the Notion of Time, Kluwer Academic Publ., The Netherlands.
- ROY, S. and KAFATOS, M. (1999) Complementarity principle and cognition process, *Physics Essays*, 12(4), 662–668.
- ROY, S. and KAFATOS, M. (2003) Quantum Processes, Space-Time Representation and Brain Dynamics, arXiv:quant-ph/0304137 v2.
- STAPP, H. P. (1993) Mind, Matter and Quantum Mechanics, Springer Verlag.
- STAPP, H. P. (1996) The hard problem: A quantum approach, J. Consciousness Studies, 3(3), 194-210.
- TEGMARK, M. (2000) The importance of quantum decoherence in brain processes, Phys. Rev. E, 61, 4194.
- UNGERLEIDER, L. G. (1995) Functional brain imaging studies of cortical mechanisms for memory, *Science*, **270**, 769–775.
- VOGGENHUBER, A. (2002) Time and binding in the cortical visual system of the macaque monkey, Thesis, University of Salzburg, Austria.
- VON DER MALSBURG, C. (1981) The Correlation Theory of Brain Function, Report 81-2, Max-Planck Institute for Biophysical Chemistry.
- WHEELER, J. A. and ZUREK, W. H. (1983) Quantum Theory and Measurement, Princeton Univ. Press.

- WHITE, J. A. and HAAS, J. S. (2003) Intrinsic Noise from Voltage Gated Ion Channels Effects on Dynamics and Reliability in Intrinsically Oscillatory Neurons, Manuscr. Dept. Biomedical Engineering, Boston Univ., U.S.A.
- WHITE, J. A., RUBINSTEIN, J. T. and KAY, A. R. (2000) Channel noise in neurons, TINS, 23(3), 131-137.
- WOLF, F. (1981) Taking the Quantum Leap, Harper and Row, San Francisco.
- ZEKI, S. (1990) Parallelism and Functional Specialization in Human Visual Cortex, Cold Spring Harbor Symp. Quantitative Biology, LV, 651–661.
- ZEKI, S. and SHIPP, S. (1988) The functional logic of cortical connections, Nature, 335, 311.
- ZHOU, Y., MORAIS-CABRAL, J. H., KAUFMAN, A. and MACKINNON, R. (2001) Chemistry of ion coordination and hydration revealed by a K⁺ channel-fab complex at 2.0 A resolution, *Nature*, **414**, 43–48.
- ZUREK, W. H. (2001) Decoherence, Einselection, and the Quantum Origins of the Classical, Archiv:Quant-ph/ 0105127 v1.